Energy Generation using Piezo Film (II)

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The following text was originally intended to form an introduction to the concept of piezo film as a power source, but the article was never completed nor formally published. As the company name has changed more than once since 1991, a brief history of the piezo film group is outlined below.

Division History:

1969: Kawai discovers high piezoelectric effect in PVDF.

1976: Pennwalt Corporation funds basic R&D activity in piezoelectric PVDF.

1982: Pennwalt establishes new Business Venture in Kynar® Piezo Film, based at King of Prussia, PA, later moving to Valley Forge, PA.

1984: Syrinx Innovations Ltd established in Edinburgh, UK as European sales office and development center - later renamed as Pennwalt Piezo Film Ltd.

1990: Elf Aquitaine acquires Pennwalt Corporation and forms Elf Atochem North America. Piezo Film group changes name to Atochem Sensors Inc (Atochem Sensors Ltd in UK).

1993: AMP Incorporated acquires Piezo Film Sensors Division from Elf Atochem. Piezo Film Division renamed AMP Sensors. European office moves to Stanmore, within headquarters of AMP of GB.

1995: AMP establishes Sensor Competency Center in Bensheim, Germany

1998: Measurement Specialties, Incorporated acquires Sensors Division from AMP Inc. Sensor Products Division remains at Valley Forge, PA, with European office near Frankfurt, Germany.

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Energy Generation using Piezo Film

Richard H Brown

1) Introduction

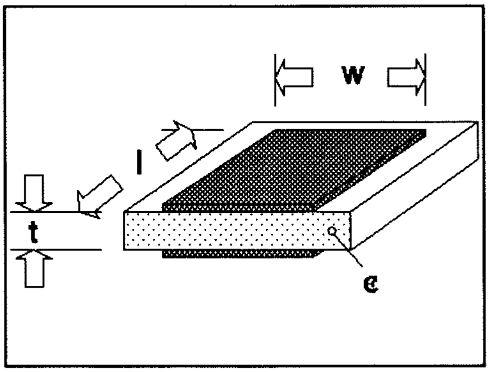
At first glance, piezoelectric polyvinylidene fluoride may not seem like a prime contender for an energy source. It is well-known to demonstrate a high voltage sensitivity to stress, yet is more often used to explore the lower end of its dynamic range, where minute vibration signals are faithfully transformed into their "signal-level" electrical analogues. At the upper limit, however, where the film is taken close to its breaking point, quite respectable energy density may be achieved. The need to push stress to the limit implies that such events are usually transient and not continuous, hence the selection of "energy" and not "power" in the title.

2) Capacitance

Piezo film components are most frequently supplied with metallized or printed conductive electrodes on upper and lower surfaces of the polymer "substrate". These electrodes serve to gather the charge generated when the film is stressed, or conversely, to apply an electric field to generate stress in the polymer.

Areas of unmetallized film do not, obviously, contribute to the electrical behaviour of the film. Areas where upper and lower metallizations do not overlap may act as transmitters or receivers of electromagnetic radiation, and so cannot be ignored.

Two metallic electrodes spaced by an insulating or dielectric material lead naturally to the consideration of film capacitance. The permittivity of the film is very high (by polymer standards) and, in fact, the non-piezoelectric form of Kynar is used for specialised capacitors where very high levels of charge must be stored for short periods of time.



The capacitance of a general piezo film element may be expressed as

$$C = \epsilon . A/t$$

where ϵ = permittivity of the dielectric (film),
A = surface area of overlapping electrodes
and t = thickness of the dielectric (film).

The term ϵ may be expressed as the product $\epsilon_0 \epsilon_r$,
where ϵ_0 = permittivity of free space
and ϵ_r = relative permittivity of the film.

$$\epsilon = \epsilon_0 \epsilon_r = (8.854 \times 10^{-12}) \times 12 \text{ F/m} = 106 \text{ pF/m}.$$

The standard thicknesses of piezo film produced by Pennwalt are:

9, 28, 52 and 110 micrometers (10^{-6} m, µm, or "microns")

Measuring the capacitance of a piezo film component is an excellent way of checking the condition of a device; occasional problems such as broken leads, split or shorting film or even unknown (forgotten!) film thickness can readily be identified with a little practice.

3. Voltage Mode

Although piezo film may be regarded either as a charge or a voltage source, it is perhaps easier to choose the latter for frequency response analysis first, and then consider the charge mode when looking at the effects of capacitive loading or film energy output.

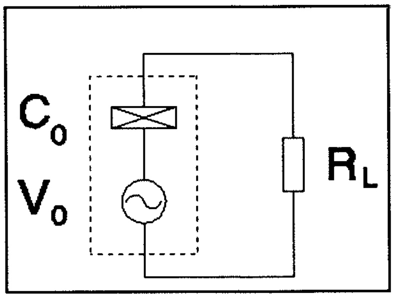
We can model the film as being a pure capacitor connected in series with a voltage source where the voltage generated is proportional to applied stress (or strain). We can say that the open-circuit output voltage is given by:

$$V_0 = g_{3n} X_n t \qquad (n = 1, 2, 3, t \text{ or } h)$$

where g is the appropriate piezoelectric coefficient,
X is the applied stress in the relevant direction,
and t is the film thickness.

The film capacitance can be measured or calculated as described above, and therefore the energy, W_0, is given by:

$$W_0 = \tfrac{1}{2} C_0 V_0^2$$



Now, to measure the open-circuit voltage, we must connect a measuring instrument across the film. The instrument is very often an oscilloscope, where the load presented appears primarily resistive and is typically 1 megohm. (The small capacitance of the probe need not concern us if the film element is reasonably large, and lower frequencies are being considered.)

The effect of applying this resistive load R_L is to form a potential divider, where the fraction of generated voltage actually seen by the measuring instrument will vary with frequency, as the impedance of the capacitor (film) varies.

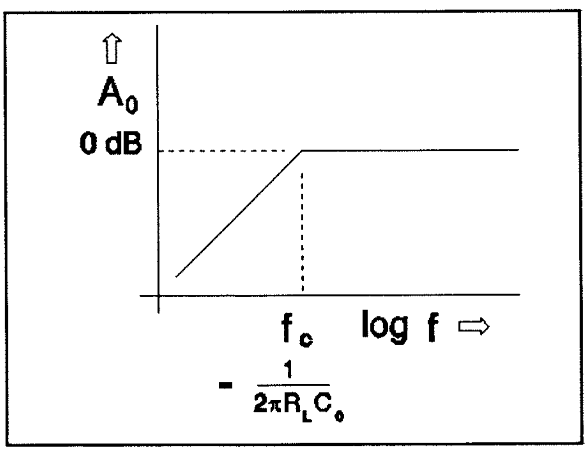
The voltage measured across the resistance, V_L, as a function of frequency, f, is given by

$$|V_L| = V_0 / \sqrt{(1+(2\pi f R_L C_0)^{-2})}$$

where V_0 is the open-circuit output voltage as above.

The network becomes a high-pass filter, where the cut-off or -3 dB frequency is given by

$$f_c = 1 / 2\pi R_L C_0$$



At frequencies sufficiently far above f_c, $V_L = V_0$, and so voltage measured is directly proportional to stress.

At frequencies sufficiently far below f_c, $V_L << V_0$ and the measured voltage is proportional to the rate of change of stress (we have a "differentiator").

What does "sufficiently far" mean? For magnitude (amplitude) measurements, perhaps one decade of frequency away from f_c should give reasonable approximations, but for phase response, allow two decades.

In practice, the very high open-circuit voltages generated by piezo film elements mean that resistances higher than 1 Megohm need to be employed to prevent overload of the measuring device. Very simple resistive dividers can be used.

4) Charge Mode

The charge generated by the film under stress is expressed in terms of charge density per unit area. Great care must be taken to avoid confusing the area under stress with the area of charge generation, since these two quantities are almost invariably different. Only when the **electrode** area exactly matches the **stressed** area are these the same.

We can say that

$$D = Q/A = d_{3n}X_n \qquad (n = 1, 2, 3, h \text{ or } t)$$

where
- D = charge density generated
- Q = charge developed
- A = metallized electrode area
- d = appropriate piezoelectric coefficient
- X = stress applied in relevant direction

5) Piezo Coefficients

Piezo film may be stressed in three different axes, and the nett efficiency is different for each. Sensitivity is expressed as voltage (or charge) sensitivity as developed across the thickness of the film for applied stress in any of the three, and is denoted by the following conventional subscripts:

"31" for stress applied along the stretch or machine axis

"32" for stress transverse to the stretch direction, and

"33" for stress in the thickness direction.

The first two cases are straightforward in their application, but the last, "33", requires further comment.

If a large sheet of film is stressed between two small radiussed indenters at a given point, the "33" coefficient is valid. If, however, the entire sheet is stressed between two flat surfaces, then the film is effectively clamped, and the "t" or clamped thickness coefficient must be used. This is lower than pure "33", and also lower than "31". Finally, if hydrostatic stress is applied (equal in all directions), then the "h" coefficient applies, which is different again.

A word about the polarity of the coefficients - it will be noted that "31" and "32" are positive, while "33" is negative. If a positive stress is given in the stretch direction (pushing, not pulling), then the film must become shorter, and fractionally thicker. A positive signal results on the positive-marked surface electrode. Positive stress applied to the thickness serves to

decrease the thickness, and so a negative signal is seen on the + electrode. Pulling in the length direction is equivalent to pushing in the thickness direction, and the polarity of the coefficients reminds us of the sign of the applied effort. Note also that positive thermal input (heating) increases the thickness and gives a positive signal on the + electrode.

6) Mechanical Constraints

Going beyond the magnitude and sign of the various piezoelectric coefficients, there is a further important aspect to the question of direction of applied stress. The breaking and yield strengths in each axis are different, and the simple fact is that stress may be applied to higher level in the machine direction than in any other. Thus, despite the attraction of the higher "33" coefficient, it is probable that more energy can be extracted (per unit volume) from a "31"-mode system.

In general, the failure mode of the film in "32" and "33" senses is splitting along the "grain" or stretch direction. This is a natural consequence of uniaxial stretching. Any compliance of the support structure when "33" is attempted will allow hybrid deformation: this can be exploited when large signals are required from ostensibly "3" or z-axis stress. Supporting an element of film between two thick layers of, for instance, low durometer rubber will convert "3" to "1" and "2" almost totally. "31" failure is more difficult to achieve, and shows more plastic deformation than the other modes.

7) Linearity

When a piezo film element is taken near to breaking point, the applied stress tends to reduce the thickness of the film, and so there is a tendency for its capacitance to increase. This effect is more noticeable with thinner films. As this happens, the relationship between observable charge and voltage alters. Under extreme stress, it is possible that the open-circuit voltage developed by the film would cease to rise with increasing stress, and could even begin to fall, due to the "overtaking" by the rising capacitance. This effect has been seen, and the results suggest that the capacitance increase is far higher than would be possible for a simple change in thickness. In fact, the capacitance of a piezo film element can more than double for quite modest applied stress. Thus the permittivity of the dielectric is also affected by stress.

It has been found in early explorations that the **charge** appears linear with applied force when the film is stressed in the machine axis, but the **voltage** maintains linearity in compression. In any event, the result is to make precise energy calculations difficult

when the film is observed directly. In most cases, the final energy level achieved is best judged from a system, rather than a component, standpoint. That is, the power dissipated by the load can often be measured more accurately than that generated initially by the film.

8) Energy Targets

As hinted at above, the energy available from a given piece of film is proportional only to the **volume** of film used, and the stress or strain level applied. However, for a given volume of film, the **format** of the electrical signal may be varied. It is possible to generate a low voltage from a high capacitance source, or vice versa. If high voltages are required, then thick film(s) and/or series-wired stacks are appropriate; conversely, parallel-wired stacks or long, wound elements will achieve more manageable voltages from a higher source capacitance. Appendix A shows a worked example illustrating the energy equivalence of the two different approaches.

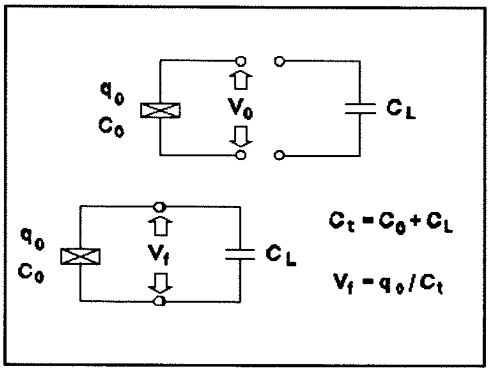
It has been found by experiment that an energy level of 200 kJ/m^3 may be realised. This is measured as a final stored energy in a capacitor, and not as an interpolated "open-circuit" energy. This figure, however, implies stress levels applied to the film well in excess of the quoted maximum strength for a short duration. In many cases, it is preferable to aim for lesser levels, with greater statistical confidence. A figure of 20 kJ/m^3 lies within the predicted capabilities of the film.

Thus, from a cubic centimeter of film, we can expect 200 mJ as an upper limit, or 20 mJ with comfort, assuming efficient design of the electrical network.

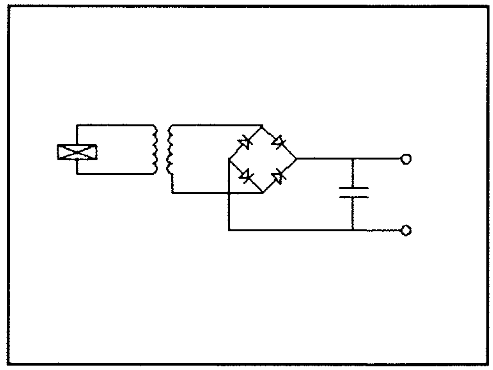
9) Electrical Matching

Transfer of the generated electrical energy from the film to the desired load is a matter of prime concern. Once the mechanical design of the transducer is complete, the electrical behaviour of the film may be approximated as a capacitor in series with a voltage source (proportional to applied stress or strain) or as a capacitor in parallel with a current source.

It is often desired to use the film to charge a separate, discrete capacitor to a defined voltage, where the storage capacitor may be orders of magnitude higher in value than the source (film). In this case, it is well worth the effort of calculating the resulting energy for a fixed quantity of generated charge. If the storage capacitor is ten times the value of the inherent film capacitance, and the two are connected directly, then the final energy level will be less than 9% of the "open-circuit" level.



In such cases, a possible solution is to match the load to the source impedance by means of a transformer. The design of the transformer depends on knowledge of many factors, not least being the bandwidth of the mechanical input. Practical transformers (physically small, low cost) are only applicable for fast waveforms. With a well-designed transformer, the resistive losses in the windings are kept low, but balanced against the required inductance levels. The coupling factor (ideally unity for most power transformers) may be varied to improve the frequency response matching of the network to the mechanical input.



Finally, the storage capacitor for fast systems should possess low effective series resistance and inductance, since charging currents may become very significant.

In other circumstances, it may be desired to dissipate the electrical energy directly into a resistive load. For low resistances, the voltage and current waveforms become proportional to the rate of change of stress on the film, rather than proportional to the stress itself. Once again, knowledge of the expected input waveform is of great importance, since the behaviour of the transducer will be strongly dependent on frequency. Numerical integration of the current waveform will yield good correspondance to the applied stress if the bandwidth of the input signal is well within the -20 dB/decade slope region of the frequency response curve. Conversely, the stress waveform may be differentiated to predict the resulting current.

10) The Input Quantity

Relating electrical output signals to a particular input parameter can be confusing. Piezo film responds, or will appear to respond, to stress, strain, force, pressure, acceleration, momentum, kinetic energy, etc. Of course, all of these quantities are interrelated. The fact is that the film is governed by stress/strain (these cannot be separated), but these quantities are extremely difficult to measure directly in most high-energy situations. It has been shown above that hybrid deformations often arise, and the accurate reduction into components is not straightforward.

If the example of a drop-test is considered, where a falling mass

impacts the film, the following will be found:

1) The peak voltage or charge signals will be proportional to the peak applied force, where the force exerted is due to the deceleration of the falling mass (neglecting the non-linearity at high levels as noted above), but when different masses are employed, the constant of proportionality may change

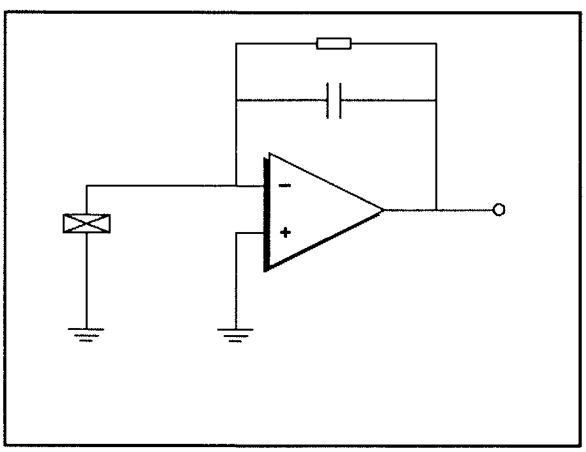
2) (more important, and easier to predict!) The integral of the resulting voltage or charge waveform is proportional to the integral of the input force, which is thus the change in momentum of the mass.

The second result follows directly from the impulse concept, where the area under the force-time curve is known, rather than the exact time of application of force or its peak value. Measured values agree very well with the calculated momentum change for falling bodies. The velocity of the mass just before impact can be deduced from its height, and if the mass does not bounce, then its final velocity will be zero.

For a system where a known mass is constantly acting on the film (as in an accelerometer) the same principle applies: the peak output will be proportional to the peak force, and thus the peak acceleration, but the final signal output may be better understood by considering integrals. In this case, the integration of the acceleration curve will give velocity, and it is the change in velocity from start to end which gives the change in momentum of the mass.

11) Circuit suggestions

For monitoring analogue signals generated by the film, the following basic op-amp circuits are useful.



The charge amplifier network allows all the charge generated by the film to be transferred to the feedback capacitor. This allows great freedom in selecting sensitivity and low-frequency roll-off. The film is presented with a short-circuit, so no potential difference exists across the connecting wires. This gives some immunity to RF interference, but the use of shielded cable is still recommended.

The feedback resistor is needed to define the LLF and thus avoid saturation.